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THESIS

**ANALYSIS OF RELIABILITY ESTIMATIONS AND
SPARES PROTECTION LEVELS ON LIFE CYCLE COSTS
OF THE MARINE CORPS H-1 UPGRADES PROGRAM**

by

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June 2004

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LEVELS ON LIFE CYCLE COSTS OF THE MARINE CORPS H-1 UPGRADES
PROGRAM**

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ABSTRACT

The purpose of this thesis is to analyze the relationship between predicted system reliability and planned spare parts levels. This will be accomplished through the integration of factors impacting spare parts levels and Life Cycle Costs into a spreadsheet model that will establish the appropriate relationship between the factors. This thesis will then attempt to determine the impact that varying estimations of reliability will have on both Life Cycle Costs and spares levels for the H-1 Upgrades Program.

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LIST OF ACRONYMS

ACE.....	Aviation Combat Element
ADT.....	Administrative Delay Time
AFMC.....	Air Force Material Command
AH.....	Attack Helicopter
AIMD.....	Aviation Intermediate Maintenance Department
Ao.....	Operational Availability
ARROW.....	Aviation Retail Requirements Oriented to WRA
AVDLR.....	Aviation Depot Level Repairables
BCM.....	Beyond the Capability of Maintenance
BFM.....	Budgeting and Financial Management
CAIG.....	Cost Analysis Improvement Group
CCAD.....	Corpus Christi Army Aviation Depot
COTS.....	Commercial Off The Shelf
D-Level.....	Depot Level
DLR.....	Depot Level Repairable
DoD.....	Department of Defense
DPML.....	Deputy Program Manager For Logistics
DT.....	Developmental Test
DTC.....	Design-To-Cost
EMD.....	Engineering, Manufacturing, and Development
FMC.....	Full Mission Capable
FOM.....	Figure of Merit
FY.....	Fiscal Year
FYDP.....	Future Years Defense Programs
GEAE.....	General Electric Aircraft Engines
HMH.....	Marine Heavy Helicopter Squadron
HMLA.....	Marine Light Attack Helicopter Squadron
HMM.....	Marine Medium Helicopter Squadron
I-Level.....	Intermediate Level
IMC.....	Intermediate Maintenance Concept
IPT.....	Integrated Product Team
ISP.....	Interim Support Period
KPP.....	Key Performance Parameter
LCC.....	Life Cycle Cost
LDT.....	Logistics Delay Time
MAG.....	Marine Aircraft Group
MAGTF.....	Marine Air Ground Task Force
MALP.....	Marine Aviation Logistics Plan
MAW.....	Marine Air Wing
MC.....	Mission Capable
MCAS.....	Marine Corps Air Station
MDAP.....	Major Defense Acquisition Program
MDT.....	Mean Maintenance Down Time
MEU.....	Marine Expeditionary Unit

MTBCF.....Mean Time Between Critical Failure
 MTBD.....Mean Time Between Demands
 MTBF.....Mean Time Between Failures
 MTBM.....Mean Time Between Maintenance
 MTTF.....Mean Time To Failure
 MTTR.....Mean Time To Repair
 NADEP.....Naval Aviation Depot
 NALCOMIS.....Naval
 Aviation Life Cycle Operational Mission Information System
 NAMP.....Naval Aviation Maintenance Plan
 NAS.....Naval Air Station
 NAVAIR.....Naval Air Systems Command
 Non-RFI.....Not Ready For Inspection
 NPV.....Net Present Value
 O-Level.....Operational Level
 O&S.....Operations and Support
 OEM.....Original Equipment Manufacturer
 OT.....Operational Test
 PEO.....Program Executive Officer
 PM.....Program Manager
 PMA.....Program Manager Aviation
 POL.....Petroleum, Oils, and Lubricants
 RFI.....Ready For Inspection
 ROI.....Return On Investment
 SA.....Supportability Analysis
 SDLM.....Scheduled Depot Level Maintenance
 SLEP.....Service Life Extension Program
 SPMAGTF.....Special Purpose Marine Air Ground Task Force
 T&E.....Test and Evaluation
 TAAF.....Test-Analyze-and-Fix
 TAAR.....Test-Analyze-and-Redesign
 TAD.....Temporary Additional Duty
 TAT.....Turn Around Time
 TDY.....Temporary Duty
 TEF.....Trailing Edge Flap
 TOC.....Total Ownership Cost
 T/M/S.....Type/Model/Series
 TTP.....Tactics, Techniques, and Procedures
 UH.....Utility Helicopter
 USMC.....United States Marine Corps
 VAMOSC.....Visibility and Management of Operating and Support Cost
 WIP.....Work In Process
 WRA.....Weapon Replaceable Assembly
 WUC.....Work Unit Code

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I. INTRODUCTION

A. PURPOSE

The purpose of this thesis is to analyze the relationship between predicted component reliability, planned spare parts levels, and Life Cycle Costs.

1. The Problem

In the past, Major Defense Acquisition Programs (MDAPs) have based their spare parts levels on sometimes poor estimations of reliability. This, in turn, can cause a severe shortage of spare parts after the system has been fielded. As this thesis will later relate, this inability to get the required spare parts when they are needed degrades a system's overall Operational Availability (Ao) and lowers a combat units mission readiness and effectiveness.

2. The Solution Proposed by This Thesis

When a Program is considering ways to determine spare parts levels, a variety of tools are used, but all of them must take into account an estimate of component reliability. This thesis will highlight the importance of reliability information when setting spares levels and determining the overall Life Cycle Cost (LCC) of a Program.

3. If the Problem Continues

Through the use of historical data, this thesis will attempt to show the difficulties that operating forces have endured in the past when actual reliability figures have been low compared to the estimated reliability of a system or system component. In these instances, spare parts

shortages are prevalent, which in turn leads to decreased Ao and mission readiness, and increased cannibalization.

B. DISCUSSION

In the early 1970s, the United States Marine Corps began to purchase the UH-1N and the AH-1J aircraft to fulfill the ongoing mission requirements of a utility helicopter and an attack helicopter respectively. In the mid 1970s, the Squadrons made up of each of these aircraft were consolidated to take advantage of the commonality possessed by the two airframes that included engines, rotor systems, drive trains, and more. This provided a manpower saving to the Marine Corps through reduction of maintenance personnel. During the 1980s the Marine Corps bought new variants of the AH-1, each of which subsequently had less and less commonality with the UH-1N. In an effort to rediscover the savings found in commonality between the two airframes, the USMC has combined an upgrade for the AH-1W model and a Service Life Extension Program (SLEP) for the UH-1N into a new program called the "H-1 Upgrade Program." The product of this program will be two new airframes for the utility and the attack mission, but with at least 84% component commonality between them.

Currently, the H-1 Upgrade Program is undergoing the Engineering Manufacturing Development (EMD) phase of the acquisition cycle. During this period, key assumptions and measurements are being made to predict the potential reliability of key components and the overall system. These measurements will be used to determine levels of spares required during initial fielding. This information is designed to give the Program Manager an understanding of

the O&S costs that will follow the airframes after fielding. These O&S costs can be up to 60% of the Total Ownership Cost (TOC) of a system so it is imperative that an accurate estimation be made during the program's EMD phase. For the H-1 Upgrade program, the current O&S cost estimate is over 60% of the TOC or over \$8 billion. It is at this time that the program office must "get it right" for the future of the program for both cost and readiness reasons.

Past experience within the aviation community has highlighted instances where poor estimations of system reliability has saddled system operators (the warfighters) with unnecessary delays, poor availability, or dangerous situations due to spare parts shortages. This has also lead to increased cannibalization and extended maintenance cycles. Proper estimation of reliability is imperative for accurate spares planning, but this needs to be emphasized as early as possible in the acquisition process. An attempt will be made, through this thesis, to highlight this situation to the Program Manager (PM) and others within the acquisition community responsible for spares determination.

The O&S cost prediction tools that a PM has at his disposal are the figures generated for him by his budget office based on the measurements given to him by the engineers conducting the reliability tests of the components and the system. If the PM wants to "what if..." a situation, he needs to wait while figures are regenerated through this process. Presenting this thesis and the tools developed through it to the H-1 Upgrades PM, may provide

him with an additional tool for understanding the tradeoffs that sometimes must be made in an environment of uncertainty and fiscal constraints. Additionally, this thesis will attempt to show that the greatest return on investment for any program is the direct investment in system reliability to increase Ao and reduce O&S costs during the life cycle of the system.

C. RESEARCH QUESTIONS

1. Primary Research Question

How are reliability estimations and planned spares levels related to Life Cycle Costs in a Major Program?

2. Secondary Research Questions

- What methods are being used by the H-1 Upgrade Program to improve overall reliability and availability?
- How are reliability and availability measured in general and by the H-1 Upgrade Program specifically?
- What information about reliability and availability estimations will be of greatest use to the PM to help make more informed decisions about O&S cost allocations?
- What is the impact on O&S costs, Ao, and spares levels if the flying hour rate is higher than planned, such as during surge or contingency operations?
- After system fielding, how are spare parts levels adjusted as estimations of reliability are replaced by actual reliability figures?

D. SCOPE OF THIS THESIS

The focus of this thesis is on constructing a spreadsheet model to estimate the Spares Levels and LCC of H-1 Upgrade Program critical components based on proper reliability estimations and subsequent spare parts planning. This model will be used to analyze the impact of changing reliability figures on the O&S costs and Spares Levels of the program. The historical precedence for changes in reliability figures will be made using examples from past Programs.

The scope is limited to the reliability of critical components within the H-1 Upgrade Program. The model will not attempt to take into consideration the Tactics, Techniques, and Procedures (TTPs) used by the Aviation Combat Element (ACE) within the Marine Air Ground Task Force (MAGTF) when employing the H-1 airframes.

The model is also limited by the accuracy of the information that will be entered into the model. Because the new H-1 airframes have not completed EMD or undergone fielding yet, much of the data is either projections or forecasts that may change as the program progresses. These scope limitations should not detract from the general findings and conclusions of the thesis research.

E. METHODOLOGY

The methodology used in the research of this thesis will include, but not be limited to:

- Conduct a comprehensive literature search of books, magazine articles, CD-ROM systems, and Internet-based materials.

- Conduct a comprehensive review of Government reports concerning issues with reliability, availability, spare parts planning, and critical elements of the H-1 Upgrade Program which may effect O&S costs and reliability.
- Conduct visits, telephone interviews, and email interviews with H-1 Upgrade program members and others to gather current and relevant data necessary for the realistic modeling of component and system reliability.
- Build a model using Microsoft Excel® software that incorporates as many factors as possible affecting LCC, spares levels, and protection levels for components of the H-1 Upgrade Program.
- Run multiple simulations with the model, varying reliability and other factors within realistic ranges.
- Analyze and interpret the results of the simulations and draw conclusions.

F. THESIS ORGANIZATION

1. Chapter I, Introduction

Identifies the purpose of the thesis as well as the primary and secondary research questions.

2. Chapter II, Background

Provides a basic understanding of the elements included in the H-1 Upgrade Program estimation of

reliability and planned spare parts levels. This chapter also contains a brief description of the H-1 Upgrade Program.

3. Chapter III, H-1 Upgrade Program Model and Data

Presents the methodology and logic behind the reliability, availability, and O&S cost spreadsheet model.

4. Chapter IV, Results and Analysis

Provides a discussion of the running of the simulation and analyzes the results to determine impacts on spares levels and O&S costs.

5. Chapter V, Conclusions and Recommendations

Summarizes the findings of the research, attempts to answer the research questions, and highlights areas of further study.

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II. BACKGROUND

A. CHAPTER OVERVIEW

The purpose of this chapter is to provide a basic understanding of the elements included in the H-1 Upgrade Program estimation of reliability and planned spare parts levels. This chapter also contains a brief description of the H-1 Upgrade Program.

B. H-1 UPGRADE PROGRAM DESCRIPTION

The H-1 Upgrade Program was chosen for this research for a variety of reasons. There are many current MDAPs that are wrestling with setting spare parts levels for the operations and support of their systems. The H-1 Upgrade Program, presently moving from Developmental Testing (DT) to Operational Testing (OT), is on the verge of setting spare parts levels for at least the next five years based on estimated and observed reliability of the test articles and through correlations with similar airframes.

Additionally, the H-1 Upgrade Program, with a current estimated Total Ownership Cost (TOC) of over \$14 billion, is attempting to capitalize on the use of identical components between two separate airframes to reduce overall spare parts quantities and manpower requirements. This use of identical components between two platforms has caused a greater emphasis on getting the right parts in the right quantities to the right places at the right time. Once these spare parts are funded and in place, they will require the full logistical support of the H-1 Upgrade Program Team and the Naval Inventory Control system.

Also, a Marine Corps system provides a more compact view of the overall logistics support system of the Department of the Navy (DoN) and the Department of Defense (DoD) since there are fewer aircraft and fewer bases than in other branches of the Armed Forces.

Bell Helicopter-Textron, the company selected to develop the H-1 Upgrade for the USMC, states the reasons for the decision to merge the two airframes in the following public statement:

The Marine Corps has begun the H-1 Upgrade Program to meet expanding mission requirements between now and the initiation of the Joint Replacement Aircraft program in the year 2020. The AH-1Z will replace the AH-1W and the UH-1Y will replace the UH-1N as remanufactured airframes to take advantage of the latest technologies, with improvements in crew and passenger survivability, payload, power availability, endurance, range, speed, maneuverability, and supportability.

Both new airframes will share the same four-bladed, all-composite, hingeless, bearingless rotor system and drive train. Additionally, they will share the same engines, transmissions, hydraulics, electrical systems and tailbooms. Therefore, both helicopters will share three out of five repairable items. The savings in maintenance staffing and training, ground handling and support equipment, and *spare parts inventories* are enormous, estimated to be at least \$3.9 billion over the life of the program.

This recapitalization program will result in 280 essentially new aircraft. The USMC will receive "zero-time" airframes, not just rebuilt, but remanufactured, with the latest in helicopter technology. In contrast, the only competing

program [AH-64 Apache and UH-60 Blackhawk variants] would result in 1970's vintage-technology aircraft, at a much higher price.

One portion of the above statement that this thesis would try to clarify is how sensitive this estimated \$3.9 billion savings are to the accuracy of the reliability estimations that Bell Helicopter and others have and will place upon the systems and components used to manufacture and support these new airframes.

C. THE DEFERRED MODERNIZATION CYCLE

Unfortunately, many of the decisions made in any MDAP are based on fiscal constraints rather than solely on the needs of the system operators and maintainers.

The recent trend of deferring modernization during the budgeting process is disturbing to anyone who realizes that with the decreased procurement of new systems, the aging systems being maintained by our fleet operators require greater and greater spending on O&S costs. This has been referred to as the "Aging Weapon Systems/Deferred Modernization Death Spiral" as illustrated in Figure 1.

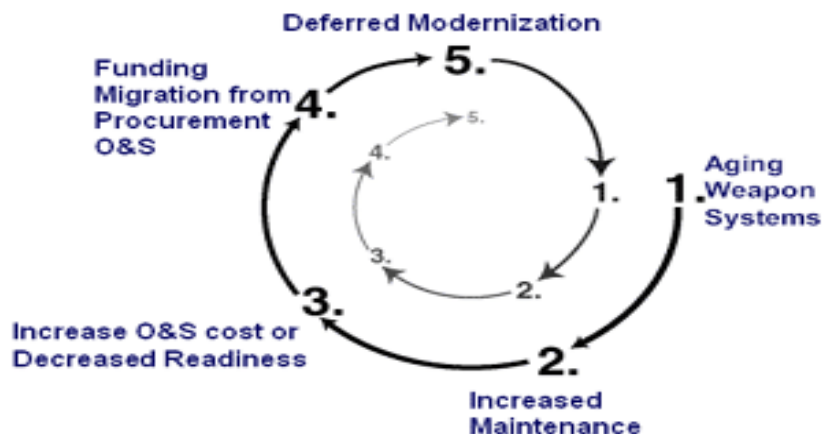


Figure 1. Deferred Modernization Cycle
[From Ref 3]

D. OPERATIONS AND SUPPORT COST BACKGROUND

How is the Life Cycle Cost (LCC) of a MDAP system calculated? The life cycle of a weapon system begins with the determination of a mission or capability requirement, continues through the engineering and manufacturing development (EMD), production and deployment, and operations and support (O&S) phases to the eventual disposal or demilitarization of the system by the government. For purposes of cost estimating, life cycle costs typically are divided into four components: research and development, investment, operating and support, and disposal. Figure 2 illustrates the program life cycle and shows how its various phases relate to the phases of a system's life cycle cost. The pattern of spending shown in Figure 2 is typical, but may not be followed by every program.

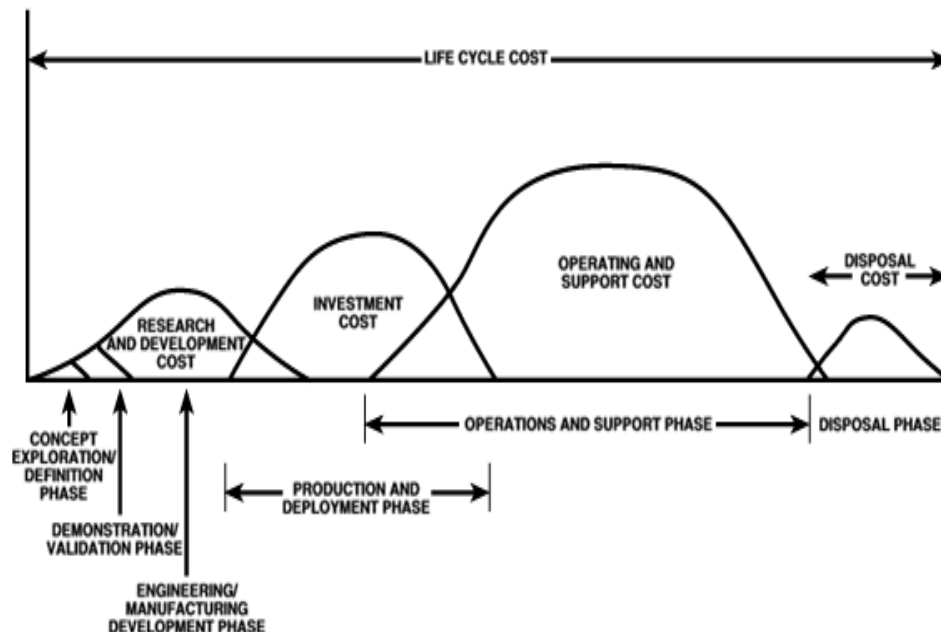


Figure 2. Life Cycle Cost Illustration
[From Ref 2]

E. OPERATIONS AND SUPPORT COST ESTIMATES

Operations and Support costs include all costs of operating, maintaining, and supporting a fielded system. Current estimated total O&S costs for the H-1 Upgrades program is over \$8 billion. O&S costs encompass costs for personnel, consumable and repairable materials, and repairs at all levels of maintenance (Operational, Intermediate, and Depot), facilities, and sustaining investment. O&S Costs are incurred in preparation for and after a system's fielding and continue through the end of the system's useful life.[From Ref 2]

The cost of operating and maintaining a system over it's useful life is driven primarily by policy, system design, operating rate or tempo (optempo), and reliability and maintainability decisions, which typically are made prior to entering production. O&S cost information is used for a variety of purposes in the acquisition process, including to:

- Support the current design-to cost (DTC) program
- Support management reviews
- Discriminate between competing systems
- Support budget estimates

While development and production estimates play a major role in decisions on the Future Years Defense Program (FYDP) and the President's Budget, O&S costs have an important, if less visible, role. This is because the support segments of the budget are organized by functional area rather than by the weapon system.[From Ref 2]

The nature of cost estimates and cost comparisons depends on the acquisition program phase and the specific issues involved. At "Milestone A", very little may be known about the design of a proposed system, but rough estimates of O&S costs are expected. In preparation for "Milestone B", O&S cost estimates and cost comparisons ought to show increased accuracy, consistent with more fully developed configurations and support concepts. As a program approaches Milestone B, the subsystem cost drivers most likely to influence O&S costs should be identified. Although the specific determinants of cost may vary by system, they can generally be grouped into three categories:

- Physical characteristics- weight, volume, density, etc.
- Policy parameters- optempo, maintenance concept, crew ratio, etc.
- Performance characteristics- power, speed, range, reliability, etc.

Alternative approaches, design trade-offs, and the sensitivity of O&S costs to change in these cost drivers should be carefully evaluated in the cost and operational effectiveness analysis.

The O&S cost estimates prepared for "Milestone C" should be based on the current design characteristics of the weapon system, the deployment schedule, and the operations and maintenance concept. Critical subsystems and any DTC goals established for them must be validated. Operating experience obtained during system test and

evaluation (T&E) should be used to verify progress in meeting logistics goals or to identify problem areas.[From Ref 2]

F. OPERATIONS AND SUPPORT COST ELEMENT STRUCTURE

As previously discussed, support segments of the budget are organized by functional area rather than by the weapon system. These cost elements are listed individually for purposes of program support, but are interdependent. A new program, or a program attempting to leverage previous program elements, such as the H-1 Upgrade program, will attempt to base much of their O&S cost estimation on historical data collected from similar Programs.

The O&S cost element structure for an aircraft system is broken down into the following numbered elements and sub-elements:

- 1.0 Mission Personnel
 - o 1.1 Operations
 - o 1.2 Maintenance
 - Organizational Maintenance
 - Intermediate Maintenance not covered elsewhere
 - Ordnance Maintenance
 - Other Maintenance Personnel
 - o 1.3 Other Mission Personnel
 - Unit Staff
 - Security
 - Other Support

- 2.0 Unit Level Consumption
 - 2.1 Petroleum, Oil, and Lubricants (POL)/Energy Consumption
 - 2.2 Consumable Material/Repair Parts
 - Maintenance Material
 - Operational Material
 - Mission Support Supplies
 - 2.3 Depot-Level Repairables
 - Depot Level Repairable (DLR) spares used to replace initial stocks
 - 2.4 Training Munitions/Expendable Stores
 - 2.5 Other
 - Purchased Services
 - Transportation
 - Temporary Additional Duty (TAD)/Temporary Duty (TDY) Payments
- 3.0 Intermediate Maintenance (External to Unit)
 - 3.1 Maintenance
 - 3.2 Consumable Material/Repair Parts
 - 3.3 Other
- 4.0 Depot Maintenance
 - 4.1 Overhaul/Rework
 - 4.2 Other
- 5.0 Contractor Support

- o 5.1 Interim Contractor Support
 - o 5.2 Contractor Logistics Support
 - o 5.3 Other
- 6.0 Sustaining Support
 - o 6.1 Support Equipment Replacement
 - o 6.2 Modification Kit Procurement/Installation
 - o 6.3 Other Recurring Investment
 - o 6.4 Sustaining Engineering Support
 - o 6.5 Software Maintenance Support
 - o 6.6 Simulator Operations
 - o 6.7 Other
- 7.0 Indirect Support
 - o 7.1 Personnel Support
 - Specialty Training
 - Permanent Change of Station Costs
 - Medical Support
 - o 7.2 Installation Support
 - Base Operating Support
 - Real Property Maintenance [From Ref 2]

Within this thesis, we will address the O&S cost elements associated with consumable material and repair parts. These elements, as you can see from the listing above, are just one of many cost drivers that must be taken into consideration by a program when structuring for a successful life cycle. This may be the reason that

estimates for reliability are not as thoroughly scrutinized, and sometimes overlooked, leading to potential problems in maintaining system operational availability levels.

G. LIFE CYCLE COST

As defined by Blanchard (1998), Life Cycle Cost involves all costs associated with the system life cycle, to include:

- *Research and Development (R&D) cost*- the cost of feasibility studies; system analyses; detail design and development, fabrication, assembly, and test of engineering models; initial system test and evaluation; and associated documentation.
- *Production and Construction cost*- the cost of fabrication, assembly, and test of operational systems (production models); operation and maintenance of the production capability; and associated initial logistic support requirements (e.g. test and support equipment development, spares/repair parts provisioning, technical data development, training, entry of items into inventory, facility construction, etc.).
- *Operation and Maintenance (O&M) costs*- the cost of sustaining operation, personnel and maintenance support, spare/repair parts and related inventories, test and support equipment maintenance, transportation and handling, facilities, modifications and technical data changes, and so on.

- *System retirement and phase-out cost*- the cost of phasing the system out of the inventory due to obsolescence or wear-out, and subsequent equipment item recycling and reclamation as appropriate.

H. RELIABILITY

"Reliability isn't everything, it's the ONLY thing!"
 [From Ref 4] This powerful statement has attempted to focus the attention of Program personnel whose job it is to make sure the systems we field are reliable for our operating forces. In focusing on reliability as it relates to the setting of spare parts levels, we must first come to understand just what is meant by reliability.

1. Reliability Expressed Mathematically

Since reliability will be the focus of this thesis as we explore historical trends in spare parts procurement, let us first define reliability in mathematical terms so we have a common frame of reference:

$$R(t) = e^{-K\lambda t}$$

R = reliability of the component or system

t = the time period of interest

e = the natural logarithm base (2.7182)

K = the number of components or systems used (sometimes expressed with the variable " n ")

λ = the failure rate of the component or system (1/Mean Time Between Failures)

With the formula above we also take into consideration the four components of reliability: probability, satisfactory performance, time, and specified operating conditions.

2. Factors Relating to Reliability

Three types of availability related to reliability are Inherent Availability (A_i), Achieved Availability (A_a), and Operational Availability (A_o). These are important as a measure of how often a component or system is ready to be used by the operator under different operating conditions. The most important factor for our research will be operational availability.

Operational Availability (A_o) is not currently a Key Performance Parameter (KPP) on many Programs, but may need to become a primary metric to measure how the fielded system is performing for the system operator.

Why is A_o such an important concept? A_o is defined as the probability that a system, when used under specified operating conditions in an actual operational environment will operate satisfactorily when required.

Mathematically, this is stated:

$$A_o = \frac{MTBM}{MTBM + MDT}$$

where Mean Time Between Maintenance (MTBM) is the reciprocal of the frequency of maintenance that includes both scheduled maintenance and unscheduled maintenance. Mean Maintenance "Down Time" (MDT) is the mean of all the recorded maintenance time that the system was unavailable for use due to either scheduled or unscheduled maintenance.

It is important to note that this expression takes into consideration ACTUAL operational conditions and ALL maintenance actions involved with the system or component.

I. DETERMINING SPARE PARTS LEVELS

Currently, the H-1 Upgrade Program is following the Marine Aviation Logistics Plan (MALP) to support the development and fielding of the system. The program has taken historical data from similar platforms and combined them to input data into the Aviation Retail Requirements Oriented to Weapons Replaceable Assembly (WRA) or "ARROW" model (a "Readiness Based Sparing Model" using operational availability as its key parameter) for determination of spares levels during the programs Interim Support Period (ISP).[From Ref 7] The ISP for the H-1 Upgrade Program is scheduled to last until the Material Support date of approximately 2010. This determination function is outsourced by the Naval Inventory Control Point (NAVICP) in Philadelphia to a private contractor who runs the ARROW model as often as necessary to meet reporting requirements.

Currently, the contractor does not have enough solid data from the Developmental Test (DT) or Operational Test (OT) aircraft to make accurate inputs into the model. It is precisely at this moment in the system life that the program office needs to emphasize accurate reliability estimates and understand the delicate balance needed to ensure adequate spares for the warfighters and adequate funding prioritization by the PM.

When designing a system, it is important to consider life cycle cost through concept, development, production, and field support. When selecting a part, one must

consider the non-recurring design cost, the recurring material cost, and the production and support costs. Each of these costs must be balanced against the others to identify the optimal part for the application. Whatever device is selected must satisfy the design-to-cost model for the system.

The following information explains the basic methods for determining spares levels.

1. Supply Support Factors

A significant portion of O&S costs go to purchase the spare parts that a system will need during the course of its time in the field with the operators and through its various levels of maintenance.

Blanchard (1998) states "supply support includes spare parts and the associated inventories necessary for the accomplishment of unscheduled and scheduled maintenance actions." [From Ref 1]

At each maintenance level, Operational (O-Level), Intermediate (I-Level), and Depot (D-Level), one must determine the type and the quantity of the spare parts to be purchased and stocked. Also, it is necessary to know how various items should be ordered and the number of items that should be procured in a given purchasing transaction.

Spare parts requirements are initially based on the system maintenance concept and are subsequently defined and justified through the Program's Supportability Analysis (SA). Essentially, spares quantities are a function of the demand rates and include consideration of:

- *Spares and repair parts covering actual item replacements occurring as a result of corrective and preventative maintenance actions.* Spares are major replacement items that are repairable, whereas repair parts are nonrepairable smaller components.
- *An additional stock level of spares to compensate for repairable items in the process of undergoing maintenance.* If there is a backup (lengthy queue) of items in the I-Level maintenance shop or at the D-Level awaiting repairs, these items obviously will not be available as recycled spares for subsequent maintenance actions; thus, the inventory is further depleted (beyond expectation), or a stock-out condition results. In addressing this problem, it becomes readily apparent that the test equipment capability, personnel, and facilities directly impact the maintenance turnaround times and the quantity of additional spare items needed.
- *An additional stock level of spares and repair parts to compensate for the procurement lead times required for item acquisition.* For instance, prediction data may indicate that ten maintenance actions requiring the replacement of a certain item will occur within a six-month period and it takes nine months to acquire replacements from the supplier. One might ask: what additional repair parts will be necessary to cover the operational needs and yet compensate for the long suppliers lead time? The added quantities will, of course, vary

depending on whether the item is designated as repairable or will be discarded at failure.

- *An additional stock level of spares to compensate for the condemnation or scrapage of repairable items.* Repairable items returned to the intermediate maintenance shop or depot are sometimes condemned (i.e., not repaired) because, through inspection, it is decided that the item was not economically feasible to repair. Condemnation will vary depending on the equipment utilization, handling, environment, and organizational capability. An increase in the condemnation rate will generally result in an increase in the spare parts requirements.

In reviewing these considerations, of particular significance is the determination of spares requirements as a result of item replacements in the performance of corrective maintenance. Major factors involved in this process are:

- The reliability of the system to be spared
- The quantity of items used
- The required probability that a spare will be available when needed (i.e., the protection level)
- The criticality of item application with regard to mission success
- Cost

2. Probability of Success with Spares Availability Considerations

Blanchard (1998) uses the following example: Assume that a single component with a reliability of 0.8 (for time t) is used in a unique system application and that one backup spare component is purchased [From Ref 1]. Using the following equation to determine the probability of the system's success having a spare available in time t (given that failures occur randomly and are exponentially distributed):

$$P = e^{-\lambda t} + (\lambda t)e^{-\lambda t}$$

With a component reliability of 0.8, the value of λt is 0.223. Substituting this value into the equation gives a probability of success of:

$$P = e^{-0.223} + (0.223)e^{-0.223}$$

or

$$P = 0.8 + (0.223)(0.8) = 0.9784$$

Assuming next that the component is supported by two backup spares (where all three components are interchangeable), the probability of success during time t is determined by the equation:

$$P = e^{-\lambda t} + (\lambda t)e^{-\lambda t} + \frac{(\lambda t)^2 e^{-\lambda t}}{2!}$$

Or through simplification

$$P = e^{-\lambda t} \left[1 + \lambda t + \frac{(\lambda t)^2}{2!} \right]$$

With a component reliability of 0.8 and a value of λt of 0.223, the probability of success is

$$P = 0.8 \left[1 + 0.223 + \frac{(0.223)^2}{(2)(1)} \right] = 0.9983$$

Thus, adding another spare component results in one additional term in the Poisson expression (the Poisson and exponential distributions are essentially equivalent in this case. For the exponential, the random variable is the time to failure, whereas it is the number of failures per a given time period for the Poisson. The exponential variable is continuous and the Poisson variable is discrete). The additional spare provides an extra 2% reliability.

3. Spare Parts Quantity Determination

Blanchard (1998) helps us understand spare parts quantity determination through the following explanation: Spare parts quantity determination is a function of the probability of having a spare part when it is needed, the reliability of the system or component, and the quantity of the components used in the system.

In determining spare parts quantities, we must consider the protection level or safety factor desired. This is the probability of having a spare part available when required. The higher the protection level, the

greater the quantity of spares required to avoid a stock-out situation. This results in a higher cost for item procurement and inventory maintenance. A higher protection level, or safety factor, is a hedge against the risk of stock-out, which could affect mission readiness or accomplishment.

When determining spare parts quantities, we must also consider system operational requirements (e.g., system effectiveness, availability) and establish the appropriate level at each location where corrective maintenance is accomplished. Different levels of corrective maintenance may be appropriate for different items. For instance, spares required to support prime equipment components which are critical to the success of a mission may be based on one factor; high-value or high-cost items may be handled differently than low-cost items; and so on. In any event, an optimum balance between stock level and cost is required. [From Ref 1]

4. Sensitivity to Reliability Changes

The issue of differences between estimated reliability and actual reliability has been a subject of debate for many years and is what prompted this thesis research. In the past, some contractors or program offices may have overestimated reliability due to the saving in support costs that could be calculated based on these higher rates, or an unexpected, significant decrease in MTBF is encountered due to unforeseen circumstances.

Within NAVAIR, a good example of the latter would be the difficulties encountered with the F/A-18 Trailing Edge Flap (TEF) hydraulic actuator. Reliability estimations for

the TEF hydraulic actuator were based on historical data from similar applications, but the system interface of the F/A-18 TEF was different than other aircraft. The TEF on the F/A-18 did not program to one position and act as a stationary flap as it did on other aircraft; the F/A-18 TEF was in constant motion as a control surface. This put greater demands on the TEF hydraulic actuator and caused a much higher than expected failure rate.

In establishing initial support for the TEF hydraulic actuator, an estimate of reliability of 4000 hours MTBF (or $\lambda = .00025$) was used by the supplier and subsequently by the F/A-18 Program office. After a period of operational service, the MTBF figure of merit was actually shown to be 900 hours (or $\lambda = .0011$). This prompted spare parts shortages and subsequent cannibalizations by O-Level maintainers to try and meet their desired operational availability for mission accomplishment. [From Ref 4]

The following highlights from an Air Force Materiel Command (AFMC) memorandum [Ref 5] showcases some of the problems identified with reliability figure uncertainty and sensitivity:

Lessons Learned

The sensitivity of Air Force operational goals (mission capability, utilization rate, sortie generation rate, etc.) to changes in reliability should be determined during design. This will enable the program office/contractor to get maximum operational payoff from increasingly scarce funding by channeling available dollars towards reliability improvements that provide the most gain in operational capability.

Problem

One system has keyed on high cost logistics support items for special emphasis in reliability improvement. It turns out that there is not necessarily a correlation between high support cost and the sensitivity of support cost to reliability changes.

Discussion

For some equipment, our reliability and demand predictions can be far from the number seen in operational use and yet have no discernable effect on combat capability or logistics support. Other equipment will have an enormous effect on combat capability, support structure, mobility, manpower, or Life Cycle Costs (LCC). The operational value of a system is proportional to its reliability or Mean Time Between Critical Failures (MTBCF). Additional benefits accrue from lower spares and maintenance demands in the field. Likewise, spares requirements may be so sensitive to Mean Time Between Demand (MTBD) that an error of a few hours can make the system unsupportable for lack of spares. Knowing, early in the design phase, the sensitivity of such things as LCC, spares, availability, etc., to reliability will permit project engineers and logisticians to know where to put the emphasis on reliability improvements, prediction accuracy, etc.

Recommended Action

In the early portion of equipment design, program managers should perform, or require the contractor to perform, sensitivity analyses of operational goals to predict reliability parameters. That equipment whose reliability parameters are shown to have large impact on the Air Force operational goals or spares requirements should receive increased engineering and management attention.

J. CHAPTER SUMMARY

The information about O&S Costs, LCC, reliability, and spares contained in the previous paragraphs will be used to highlight the problems and solutions contained in the thesis spreadsheet model described in the next chapter.

III. H-1 UPGRADE PROGRAM THESIS MODEL AND DATA

A. CHAPTER OVERVIEW

The purpose of this chapter is to expand on the concepts of reliability, LCC, and sparing presented in the previous chapter, and explain how they apply to the spreadsheet model used in this thesis. This general framework will serve to highlight the sensitivity of spares levels and LCC to all these factors.

B. THESIS SPREADSHEET MODEL DESCRIPTION

From information gathered through research, a spreadsheet model for spares levels relating to operational availability and O&S costs at the H-1 Upgrade Program has been developed. Specific components from the H-1 Upgrade Program were used to highlight sensitivity to mission critical spares areas. Data from the Reliability and Maintainability (R&M) Office at Naval Air Systems Command (NAVAIR) and information from the H-1 Legacy systems program desk for the UH-1N and the AH-1W provided historical data.

The time frame used in the model for the H-1 Upgrade Program is 20 years from Initial Operational Capability (IOC) which is estimated to be in 2007, since the Cost Analysis Improvement Group (CAIG) has recommended this figure be used for rotary wing aircraft in their O&S Cost Estimating Guide. [From Ref 2] An item of note, however, is that the AH-1Z and UH-1Y have been projected by some within the DoD to be in service for at least 30 years. This estimation is likely based on the historic precedent

of the CH-46 average service life currently approaching 40 years and the UH-1N service life approaching an average of 30 years.

Lastly, to convert constant dollars to current dollars a normal discount rate of 3.2% was used. This discount rate is the recommended rate from the Office of Management and Budget (OMB) Circular A-94 [Ref 12] for discounting costs of systems with a useful life of 20 years or more. The Budget and Financial Management (BFM) Office of NAVAIR estimates the future inflation rate will average 4% per year.

1. Assumptions within the Spreadsheet Model

The framework for the thesis spreadsheet model is based on an aviation logistics decision support spreadsheet model developed by Dr. Keebom Kang at the Naval Postgraduate School. As with any model trying to emulate the working of a real world system, some assumptions about the operating environment need to be made to limit the external variables affecting the model. Therefore, the following assumptions need to be taken into consideration when viewing the operation and results of the spreadsheet model presented here.

a. Relationship Between MTBF and Repair Turn Around Time

First, it must be assumed within this thesis spreadsheet model that all repairs being conducted on components will be done at the I-Level. This is a big assumption, but needs to be considered to make the Repair

TAT a more manageable figure. This is also reasonable when evaluating the complexity of the critical spares being used as examples in the model.

Second, we must assume that failure times follow an exponential distribution.

b. Circumstances Surrounding Component Failure

We must assume for our model that a component will only fail during operational use. This does not take into consideration the real world problems of breakage during: installation, improper testing, packing, shipping, handling, and transportation.

c. Aging Components

As any system proceeds through its life cycle, the aging of the components will tend to lead to shorter MTBF depending on whether the component is mechanical or electronic. In our model, we will assume that, while mechanical, once a component is repaired it is considered to have the same MTBF as a new component.

d. Levels of Maintenance

Within the model, we must assume that when the critical component fails, the failed item is removed from the aircraft at the O-Level. Once removed, the squadron maintenance department turns in the faulty item, referred to as Non-Ready-For-Issue (Non-RFI), to the supply department at the I-Level, or MALS. The MALS supply department, upon receipt of the Non-RFI item and a requisition for a Ready-For-Issue (RFI) spare for the squadron, then issues an RFI item from its storeroom (if one is available) and inducts the Non-RFI item into the MALS for repair. If a spare is not immediately available

(a stock-out situation), the squadron may have to wait for the Non-RFI component to be repaired, decreasing aircraft availability and mission readiness.

Upon completion of repair, having issued a RFI spare to the squadron upon turn-in, the MALS returns the now RFI item to the supply department which receives and stores the item for future issue to the O-Level.

A Non-RFI repairable item the MALS is either unable or unauthorized to repair is considered Beyond the Capability of Maintenance (BCM) and returned to the supply department for shipment to the appropriate D-Level activity for repair. When a BCM occurs, the supply department will attempt to acquire a replacement spare for the repairable item on a one-for-one basis as soon as possible from other I-Level sources or elsewhere within the Naval Supply System.

2. Actual Levels of Maintenance within Marine Corps Aviation

The following description of maintenance levels to be utilized by the H-1 Upgrade Program is necessary to understand the relationship between the formulas contained in the model and the outputs provided to the user.

In Chapter II, we outlined the levels of maintenance in place and necessary to sustain a fielded USMC aviation system. The Naval Aviation Maintenance Program (NAMP) divides aviation maintenance into the following three levels:

a. Operational Level Maintenance

O-Level maintenance is performed within the squadron that has custody of the aircraft and controls its

day-to-day operations. The goal of O-Level maintenance is to support daily squadron operations by maintaining mission readiness and achieving the highest possible operational availability. These measures are sometimes referred to as the Full Mission Capable (FMC) or Mission Capable (MC) rates.

FMC status is given to an aircraft that has all primary and secondary subsystems required for every possible mission scenario properly functioning, whereas MC status means that the aircraft has a subsystem or set of subsystems that are currently not functioning properly, but do not keep the aircraft from being flown for mission scenarios not requiring those subsystems. The FMC and MC rates are frequently used by higher headquarters as a substitute for an Ao figure in a Squadron.

b. Intermediate Level Maintenance

I-Level maintenance support for USMC aircraft is performed by Marine Aviation Logistics Squadrons (MALs) attached to each Marine Aircraft Group (MAG).

The MALs provides both direct and indirect support for the O-Level maintenance effort. The goal of their I-Level maintenance facilities is to enhance and sustain the mission capability and readiness of supported units by providing high quality and timely support with the lowest practical expenditure of scarce resources. This can be done in garrison, aboard ship, or during deployed operations.

Generally, one MALs supports one MAG, but the MALs may vary in size and organizational structure based on

the number of squadrons and the associated Type/Model/Series (T/M/S) aircraft supported.

The MALS within the rotary wing side of Marine aviation supports all the T/M/S aircraft that a MAG is fielding to support the Marine Air Wing (MAW) or the MAGTF. For example, a MALS facility at Marine Corps Air Station (MCAS) New River, North Carolina services the needs of one HMLA squadron which currently flies nine UH-1N and eighteen AH-1W helicopters, one Marine Heavy Helicopter Squadron (HMH) which flies twelve CH-53E helicopters, and three Marine Medium Helicopter squadrons (HMM) which each fly twelve CH-46E helicopters for a total of 75 aircraft. Table 1 gives a breakdown of the MALS support for the AH-1W helicopters at the HMLA.

Type of Navy Aircraft (TMS)	AH-1W
Base Year of the Analysis	2002
Number of AH-1W Aircraft in HMLA 167	18
Flight Hours per Month	20.22
NAO Officer Percentage Applied	75%
NAO Enlisted Percentage Applied	100%
Percent of Consumables Used at the Squadron	78%
Percent of Consumables Used at the MALS	22%
Percent of MALS Workload for AH-1W	11%
Number of AH-1W Squadrons at the MALS	1.5
Number of Squadrons Supported by MAG 26	6
Number of Squadrons Supported by 2nd MAW	30

Table 1. MALS AH-1W Support [From Ref 9.]

A similar table for the UH-1N aircraft supported by the MALS shows a 6% rate for "Percent of MALS workload for UH-1N." Overall, this 17% of the MALS workload taken

up by the HMLA corresponds to the percentage of AH-1Ws and UH-1Ns supported by this MALS.

During Marine Expeditionary Unit (MEU) deployments of detachments from the MAG (usually consisting of one HMM squadron augmented by one-third of an HMH and one-third of an HMLA) the MALS will send a large number of specialized personnel to augment the Navy's Aircraft Intermediate Maintenance Department (AIMD) found aboard helicopter-carrying ships. This is also true for Special Purpose MAGTFs (SPMAGTFs) that may take more or less MALS personnel and equipment depending on the force structure dictated by the mission.

c. Depot Level Maintenance

In this model, we do not consider D-Level maintenance other than to state that it is included in overall repair time of repairable spares. This is because there is not a significant impact on the operational availability of fielded systems due to work conducted at the depot other than delays caused by work in process (WIP) times. This is an additional area of study briefly touched on in this thesis that could have a major impact on operational availability and mission readiness. Currently, studies are being conducted at NAVAIR and NPS to evaluate the cost savings, increased operational availability, and enhanced mission readiness achievable through increased investment in improvements at the D-Level.

The goal of D-Level maintenance is to support O-Level and I-Level maintenance activities. This is done by performing repairs beyond the capability of maintenance (BCM) of the lower maintenance levels, usually on equipment

requiring major overhaul or rebuilding of end items, assemblies, and parts. D-Level activities are tasked to ensure the continued flight integrity and safety of airframes and related flight systems throughout their service life.

For USMC aviation assets, D-Level maintenance is usually performed at Naval Aviation Depots (NADEPs). However, an increasing trend is to contract out the D-Level maintenance to other military services or to private industry capable of performing the work.

As an example, certain components are sent to D-Level repair at the Original Equipment Manufacturer (OEM). One example of this practice is the D-Level maintenance on the T-700 engine which is done at the OEM, General Electric Aircraft Engines (GEAE). This practice has become more common because of the expertise and cost savings available at the equipment's point of origin thanks to the specialized equipment and personnel there.

3. Thesis Spreadsheet Model Input Variable Description

The following parameters are user-defined inputs into the thesis spreadsheet model:

a. Number of Aircraft

Within the thesis spreadsheet model, we need to specify how many aircraft the spares assigned to each I-Level activity (MALS) is supporting.

b. Critical Components Considered

Within the thesis spreadsheet model we will consider the maintenance of only a few components and their spares. These components will be critical, repairable

components without which the aircraft cannot operate. Chosen for this thesis spreadsheet model are the engines, combining gearbox (which takes the power generated by both engines and combines it to drive the main drive shaft), the main transmission, and the main rotor blades. How many spares will be available for each of these critical components is based on figures supplied by the H-1 program office.

c. Failure Rate

Within the model we assume that the critical component fails with a constant rate of $1/\text{MTBF}$ or λ , following a Poisson distribution. The failure rate input is based on historical data, manufacturers predicted reliability, or is an artificial figure used for comparison purposes as described in each of the scenarios.

C. O&S COSTS BREAKDOWN

Members of the H-1 Upgrade program and the NAVAIR Budget and Financial Management (BFM) office provided the O&S and component costs contained in this thesis.

While most of the costs are accurate with regard to established components, some are estimates of unit costs that may change through economies of scale or design improvements. An example of this is the General Electric (GE) T700-401 engine, which will be common to the AH-1Z and the UH-1Y, and is currently being used by the AH-1W. Additionally, average annual maintenance costs per failure are estimated for components on the Upgrade Program based on current cost per failure of similar components on the AH-1W.

D. SPARES LEVELS OF CRITICAL COMPONENTS

Critical components must be described as those without which the overall system cannot function, an example being an engine, a main rotor blade, or a transmission. Components not considered critical to operation, such as certain fasteners, electronic components, or mission kits may still degrade overall mission capability if not readily available, but will not preclude all operations.

In calculating the spare parts levels for critical components, it is important to highlight the sensitivity of the overall Life Cycle Cost to small fluctuations in reliability.

It is in this area that all members of the H-1 Upgrade program specifically and the Naval acquisition field in general, need to focus their attention while completing the test and evaluation (T&E) phase of EMD. Nowhere else can the small decisions concerning improved reliability so greatly affect the overall cost of the program.

E. PROTECTION LEVEL

Protection against stock-out is a primary concern for the logistician and must be balanced against the cost of the component. Therefore a protection level of 100% is rarely used. For higher priced components, a calculated risk must be taken to balance scarce resources against the requirement for mission success. Within the scenarios for our analysis, we will vary the protection levels to determine the impact on spares and LCC.

F. CHAPTER SUMMARY

The information provided in this chapter was meant to carry the reader from the macro view of the calculations presented in Chapter II to the more discrete application of those calculations in the spreadsheet model that will be described and analyzed in Chapter IV.

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IV. RESULTS AND ANALYSIS

A. CHAPTER OVERVIEW

This chapter will utilize the information presented in Chapters II and III to draw conclusions based on the interaction of data entered into the spreadsheet model. Additionally, detailed explanation will be given about the calculations used within the spreadsheet model.

B. SIMULATION OF H-1 UPGRADE PROGRAM MODEL

The spreadsheet model described here has the limitations and assumptions described in Chapter III. There is, however, enough detail and interaction between the variables to give a reasonable estimation of spares levels and LCC for the critical components being analyzed. The detailed description of the model will be expanded on in this discussion of discrete variable inputs.

1. User-Defined Variable Input Parameters

In the spreadsheet model, accurate user defined inputs, as explained in Chapter II, play an important role in determining whether the model will be an effective tool for determining the relationship between reliability estimations, spares levels, and Life Cycle Cost.

The parameters in the following paragraphs will be used when inserting user-defined variables and can be seen in the visual representation of the spreadsheet in Appendix A.

a. Aircraft Per Squadron (K)

The number of aircraft supported by the typical I-Level activity (MALS) should be input. An example can be

seen in Table 2. If the calculations are used to ensure spares coverage for a detachment of aircraft, then all other user-defined inputs should reflect the deployed nature of the variables.

For the analysis conducted by this thesis, we will utilize the average number of aircraft supported by one MALS, which is 18 for the AH-1W or AH-1Z, and 9 for the UH-1N or UH-1Y. However, since the AH-1Z and UH-1Y will share over 80% of their spares, spares protection levels of the critical components cited here will need to reflect the fact that they are supporting the combination of both T/M/S during calculations. For this reason, the number of aircraft being supported by the MALS will be 27 to illustrate the combination of the two T/M/S.

Type of Navy Aircraft (TMS)	AH-1W
Base Year of the Analysis	2002
Number of AH-1W Aircraft in HMLA 167	18
Flight Hours per Month	20.22
NAO Officer Percentage Applied	75%
NAO Enlisted Percentage Applied	100%
Percent of Consumables Used at the Squadron	78%
Percent of Consumables Used at the MALS	22%
Percent of MALS Workload for AH-1W	11%
Number of AH-1W Squadrons at the MALS	1.5
Number of Squadrons Supported by MAG 26	6
Number of Squadrons Supported by 2nd MAW	30

Table 2. MALS AH-1W Support [From Ref 9]

In order to calculate the cost for the entire Fleet, the "Acquisition Profile" worksheet for each component takes into consideration the entire quantity of aircraft fielded in a given FY based on the current Program purchase baseline.

b. Monthly Flight Hours (t)

This variable has a direct effect on our model as the failure rate will use this variable to generate spares levels and LCCs. We will input the average annual operating hours for the T/M/S being analyzed. Currently, the AH-1W and UH-1N are shown to have an annual operation time of 243 hours based on a monthly operation time of 20.22 hours per supported aircraft as shown in Table 2.

The Number of flight hours per month is an average, based on historical data, used by support activities to determine supportability requirements. The historical average does not take into account accelerated aircraft usage caused by contingency operations. During the course of our analysis, we will vary the monthly average flight time to determine the effect of continuous contingency operations on LCC and required spares.

c. Mean Flight Hours Between Failures (MFHBF)

Reliability figures for components must have a basis in time for their determination. Different systems use a variety of measurements such as wall clock hours, engine hours, or in our case, flight hours.

Aircraft component manufacturers usually espouse a particular MFHBF for their components as a reference that can be easily compared with the usage on the aircraft (see monthly flight hours above).

Flight hours are a fairly accurate time measurement for larger components associated with aviation operations. Their life can be tracked through the maintenance documents that associate them with a particular airframe. The flight hours are recorded by the pilots upon

their return from a given mission and entered into the aircraft's logbook through the NALCOMIS system. What this does not take into account, however, is the time that the aircraft is turning its engines and dynamic components on the ground before flight, after flight, and during test procedures.

Some components, such as some electronic devices, have built in clocks (which record the elapsed time whenever the equipment has power applied) for more accurate life cycle time measurements. The lack of accurate recorded time on the critical components studied in this thesis brings to light one of the real world variables that the model cannot duplicate.

d. Mean Time Between Failures (MTBF)

As stated above, the most common reliability figure given by an aircraft component manufacturer is MFHBF. In our spreadsheet, however, we need to convert this to a calendar reference (days) to make the association between the monthly average flight hours flown and the failure rate described below. This is done in the spreadsheet by taking the MFHBF and dividing it by the average monthly flight hours and multiplying by 30 days. The resulting figure gives the average number of days between failures of that component.

e. Failure Rate (λ)

This variable is the key to our analysis. We will input the variables used by the H-1 Upgrade Program for budgetary projections. An example of how this data is tracked is provided in Table 3. Any changes made to the

reliability estimations given by the H-1 Upgrade program for comparison in the analysis scenarios will be within +/- 20% to be reasonable.

WUC 22		Turboshaft Engines								
YEAR	FLT HRS	# Maint Actions	# Failures	MFH-BMA	MFH-BF	Failure Rate	#MMH	MMH PER FLT HR	EMT	MTTR
1990	14649	917	331	15.97	44.26	0.022596	3114	0.213	1803	1.97
1991	18546	1156	492	16.04	37.69	0.026529	5606	0.302	2731	2.36
1992	26081	1257	514	20.75	50.74	0.019708	7147	0.274	2840	2.26
1993	23453	1245	506	18.84	46.35	0.021575	6887	0.294	2648	2.13
1994	29885	2156	734	13.86	40.72	0.024561	9331	0.312	4499	2.09
1995	34952	2770	955	12.62	36.60	0.027323	11551	0.330	5798	2.09
1996	33171	3268	986	10.15	33.64	0.029725	13123	0.396	7792	2.38
1997	31602	1675	811	18.87	38.97	0.025663	9228	0.292	3461	2.07
1998	35508	1914	994	18.55	35.72	0.027994	8136	0.229	3542	1.85
1999	36208	2569	1148	14.09	31.54	0.031706	10750	0.297	4746	1.85
2000	37124	2008	948	18.49	39.16	0.025536	8102	0.218	3768	1.88
2001	37484	1790	867	20.94	43.23	0.023130	10130	0.270	3896	2.18
Average	29888.58	1893.75	773.8333	16.59797	39.88519	0.025504	8592.063	0.285608	3960.333	2.091367

Table 3. AH-1W GE T700-401 Engine Reliability and Maintainability History [After Ref 14]

Additionally, the estimations of reliability for the improved engines and other dynamic components in our analysis being procured for the H-1 Upgrade Program are still under evaluation as the AH-1Z and UH-1Y undergo Operational Testing. Therefore, the estimated MTBF figures used in the comparative scenarios are based upon information gleaned from the prime contractor and the program office.

f. Repair Turn Around Time (TAT) in Days

This user defined input is based on historical figures such as those provided by the H-1 Program for T-700 engines in Table 3, and will vary for different components.

g. Failure Per Squadron During TAT

These calculations are generated by multiplying the number of aircraft in a squadron by the failure rate

and then multiplying by the Repair TAT. This is our first indication of whether sparing will keep pace with demand. If the number is less than one, then the pipeline numbers will remain low because the repairable component inducted by the MALS will be returned to the shelf before the next incident of component demand, reducing the probability of a stock-out situation.

h. Failures Per Squadron Per Year

Taking the calculation for one calendar year divided by MTBF (converted to days) and then multiplied by the number of aircraft per Squadron will give us the estimate for the number of component failures the squadron should expect during the year. This calculation will be used to multiply by the cost per repair to build the overall LCC for each component.

i. Protection Level

This user-defined input is based on the level of risk acceptable to the procuring activity for determining how many spares will be procured to avoid a stock out condition. The higher the protection level, the higher the cost to procure the number of spares required for the desired in-stock levels.

Generally, the dynamic components discussed in this thesis will have a protection level of 85%, which is the baseline protection level of expensive critical components. During the course of our analysis, we will vary this figure to highlight its impact on LCC.

j. Required Spares Based on Poisson Calculation

This figure is used as a comparison to actual spares purchased. The calculation is based on the variable

input by the user, which is then translated into the Poisson calculation on the back worksheet of the overall spreadsheet model.

A Poisson table is included for the calculation of this figure.

k. Unit Acquisition Cost

This user-defined input is taken from cost estimations provided by the program office. For components without a current equivalent in another platform, the historical data for the UH-1N and AH-1W or from cost estimates for the UH-1Y and AH-1Z provided by the H-1 Upgrade program will be input. Realistically, this cost could change in the future, affecting O&S costs, through price increases from technical difficulties or price decreases through economies of scale, etc.

l. Average Annual Maintenance Cost Per Failure

The figures inserted into this field are based on support costs paid by NAVICP for each D-Level failure of the component being analyzed. This user-defined input is taken from historical data provided by the H-1 Upgrade Program. It describes the costs to the program for overhead associated with developing I-Level maintenance support for the component being analyzed. This variable will be held constant throughout our analysis.

m. Average Total Annual Maintenance Cost

This figure is based on the average annual maintenance cost listed above times the failures per squadron per year and on historical data provided by the H-1 Upgrade Program. It is the annual cost associated with I-Level maintenance support for the component being

analyzed. This variable will be held constant during our analysis, but could vary greatly and affect LCC should technical difficulties increase this variable or support improvements decrease it.

n. Initial Spares Purchase Cost Per Squadron

This figure is the number of spares required per squadron multiplied by the acquisition cost per unit. This will feed into the LCC figure described below.

o. Total Component 20 Year LCC

The figure displayed in this cell is a sum from the Acquisition Profile sheets for each component. This is the second metric that will display the sensitivity of changes in reliability.

The magnitude of these figures were staggering at first, until I realized that these cost were covering maintenance and spares for an entire fleet of aircraft over their service life. Unfortunately, higher headquarters personnel who want to produce the most capability with the smallest investment rarely consider this high cost. Hopefully, this thesis will give a glimpse of these costs and help us all understand that an investment in reliability makes fiscal and operational sense for the warfighters and the budget analysts.

p. Fiscal Year and Years of Operation

These place-marks will help us to track the program over time and understand the cost growth as new aircraft are added to the inventory, steady out, and then decline as retirement takes place.

q. *Total Aircraft Produced Per Year*

This figure will be a representation of the total number of AH-1Z and UH-1Y aircraft purchased by the Marine Corps during each fiscal year. The cumulative number is used because the components being discussed are common to both platforms.

r. *Total Aircraft Inventory*

The figure in this cell is the total aircraft expected to be in service during the fiscal year cited. This is important because the spares levels need to be matched to the entire fleet of aircraft rather than just those purchased that year.

s. *I-Level Spares Purchased During Fiscal Year*

This figure is the number of spare components that will need to be purchased per squadron as they are stood up. All the items are repairable, but must continue to be purchased (at a slower rate) after all squadrons have been stood up due to attrition.

t. *Initial Spares Purchase*

The figure use on the "Acquisition Profile" worksheets are the same as the figures use on the "Analysis" worksheet, but will be used to generate the LCC of the individual components.

This figure is the acquisition cost of the spares multiplied by the number of spares purchased in the given fiscal year.

u. Annual Maintenance Cost

This figure is the annual maintenance cost of the particular component associated with all the aircraft that are currently fielded in the fiscal year cited by the estimate.

v. Total Cost (FY2004)

This cost is the simple addition of the Initial Spares Purchase Cost and the Annual Maintenance Cost for the fiscal year being cited. This cost will then be modified through proper accounting method in the following cells.

w. Cost with Inflation (Then Year)

This figure takes into consideration the Inflation Rate mentioned below. It is important to understand the costs that will take place in each fiscal year and how they are estimated to increase as they get further and further out from the present.

x. Present Value (FY2004)

This is equivalent to the value if the costs were paid today to meet the needs of the future warfighters. It is the sum of these values over the total fiscal years cited that will give us our Net Present Value listed below.

y. Net Present Value (NPV)

The Net Present Value is the sum of the Present Value figures mentioned above and will also be interpreted as the LCC for the component being analyzed. This total gives the Program Manager and logisticians on the H-1 Program a snap-shot of what price we would pay for all the spares and their maintenance if we had to put all the money down today.

z. Inflation Rate

This user-defined input is derived from an estimate of inflation in the United States which the H-1 Upgrade Program will have to contend with during all of its budgeting. The program is currently using an inflation estimate of 4%.

aa. Discount Rate

The discount rate input into the spreadsheet calculations here is based on the discount rate recommended by the Office of Management and Budget (OMB) Circular A94. [From Ref 12]

C. SCENARIOS USED FOR COMPARATIVE ANALYSIS

To limit the amount of variables being changed during each analysis, the analysis of the spreadsheet model was broken down into four scenarios:

- **Scenario 1:** By using present estimations of MTBF, program provided O&S costs, and other support inputs in relation to the components for the AH-1Z and UH-1Y, we will derive a baseline LCC for comparison with scenarios 2, 3, and 4.
- **Scenario 2:** In order to determine the significance of a higher than expected failure rate (lower MTBF or decreased reliability) on the spares level protection and LCC, we will use scenario 2 as a contrast to the estimated figures presented by the program office in scenario 1. This will highlight the changes in spares levels and O&S costs of a 20% decrease in the reliability of each of the components analyzed.

- **Scenario 3:** This scenario will use scenario 1 baseline reliability figures and cost, but utilize higher protection levels to highlight the price of bringing higher operational availability (FMC/MC rates) to the warfighters.
- **Scenario 4:** In this scenario we will attempt to analyze the impact of an increase in flight hours that could occur during sustained contingency operations (similar to the current Global War On Terrorism). This will be broken down into two parts:

1. Scenario **4a**, which will be using scenario 1 reliability figures.
2. Scenario **4b**, which will use scenario 2 figures to highlight the potentially compounding problem of less reliable components being used more often than expected.

1. Scenario 1: Current Estimates of Reliability, Peacetime Operational Tempo

To have a foundation for the comparative analysis in this thesis, the use of H-1 Program provided reliability and cost data allows a benchmark to be set. Many of these values are taken from historical data associated with the AH-1W because there is not enough data available on the systems currently being flown on the AH-1Z and UH-1Y.

a. Scenario 1 User-defined Input Values

The user-defined inputs below will describe the values dictated by the given scenario.

There are two separate worksheets that are described here in scenario 1, specifically the "Analysis" worksheet and the "Acquisition Profile" worksheet. The user-defined inputs on the acquisition profile worksheet will not change from scenario to scenario due to the current H-1 Upgrade acquisition program baseline (how many aircraft and spare parts will be purchased during a given year) being unchanged with the scenario variables selected.

- Number of Aircraft* (combined AH-1Z Cobras and UH-1Y Hueys per HMLA due to shared components): 27

** will not change between scenarios*

- Monthly Flight Hours (per aircraft): 22
- MFHBF in hours:
 - Engine: 100
 - Combining Gearbox: 2500
 - Transmission: 5000
 - Main Rotor Blades: 550
- MTBF (in days, calculated from MFHBF):
 - Engine: 136.36
 - Combining Gearbox: 3409.09
 - Transmission: 6818.18
 - Main Rotor Blades: 750
- Failure Rate per day (λ , calculated from MTBF):
 - Engine: 0.00733

- o Combining Gearbox: 0.00029
 - o Transmission: 0.00015
 - o Main Rotor Blades: 0.00133
- Repair TAT in days*:
 - o Engine: 5
 - o Combining Gearbox: 45
 - o Transmission: 60
 - o Main Rotor Blades: 30
- * *will not change between scenarios*
- Expected Number of Failures/Squadron during TAT:
 - o Engine: 0.99
 - o Combining Gearbox: 0.36
 - o Transmission: 0.24
 - o Main Rotor Blades: 1.08
- Expected Number of Failures/Squadron/Year:
 - o Engine: 72.27
 - o Combining Gearbox: 2.98
 - o Transmission: 1.45
 - o Main Rotor Blades: 13.14
- Target Protection Level for Each Component:
 - o Engine: 0.85
 - o Combining Gearbox: 0.85
 - o Transmission: 0.85

- o Main Rotor Blades: 0.85
- Unit Acquisition Cost*:
 - o Engine: \$695,000
 - o Combining Gearbox: \$476,000
 - o Transmission: \$930,000
 - o Main Rotor Blades: \$233,000
- Average Annual Maintenance Cost/Failure*:
 - o Engine: \$85,000
 - o Combining Gearbox: \$50,000
 - o Transmission: \$200,000
 - o Main Rotor Blades: \$15,000
- * *will not change between scenarios*
- Total Aircraft Produced/Year*: see tables 8 and 10, Appendix A
- Initial Spares Purchased*: see tables 8 and 10, Appendix A
- Inflation Rate*: 3.2%
- Discount Rate*: 4.0%
- * *will not change between scenarios*

These values were placed in the appropriate cells in the analysis and the acquisition profile worksheets of the spreadsheet model depicted in Appendix A and provide the following results.

b. Scenario 1 Analysis Worksheet Output

The calculations incorporated into the spreadsheet to develop the user-defined values into the required spares and the LCC provided the following critical component analysis.

- Required Spares: (calculated from the relation between Failures/Squadron during TAT and Protection Level)
 - o Engine: 3
 - o Combining Gearbox: 1
 - o Transmission: 1
 - o Main Rotor Blades: 3
- Sparing Based on Poisson Calculations:
 - o Engine: 2
 - o Combining Gearbox: 1
 - o Transmission: 1
 - o Main Rotor Blades: 2
- Average Total Annual Maintenance Cost:
 - o Engine: \$6,142,950
 - o Combining Gearbox: \$144,540
 - o Transmission: \$289,080
 - o Main Rotor Blades: \$197,100
- Initial Spares Purchase Cost/Squadron:
 - o Engine: \$2,085,000
 - o Combining Gearbox: \$476,000

- o Transmission: \$930,000
 - o Main Rotor Blades: \$699,000
- Total Component 20 Year LCC:
 - o Engine: \$187,930,428
 - o Combining Gearbox: \$22,704,857
 - o Transmission: \$38,086,790
 - o Main Rotor Blades: \$38,041,454
- Combined 4-Component LCC: **\$286,763,529**

The tables in Appendix A are taken from this scenario and provide a visual representation of the figures above. Analysis of these figures is provided in paragraph D "Analysis of Results" below.

2. Scenario 2: Decreased Reliability, Peacetime Operational Tempo

In order to determine the significance of decreased reliability (a higher than expected failure rate or lower MTBF) on the spares level and component LCC, we will use scenario 2 as a contrast to the estimated figures presented by the program office in scenario 1. This scenario will highlight the changes in spares levels and O&S costs of a 20% decrease in the reliability of each of the components analyzed.

a. Scenario 2 User-defined Input Values

Only user-defined input values that have changed between scenario 1 and scenario 2 will be noted.

- MFHBF in hours:
 - o Engine: 80

- o Combining Gearbox: 2000
 - o Transmission: 4000
 - o Main Rotor Blades: 440
- MTBF (in days, calculated from MFHBF):
 - o Engine: 109.09
 - o Combining Gearbox: 2727.27
 - o Transmission: 5454.55
 - o Main Rotor Blades: 600
- Failure Rate per day (λ , calculated from MFHBF):
 - o Engine: 0.00917
 - o Combining Gearbox: 0.00037
 - o Transmission: 0.00018
 - o Main Rotor Blades: 0.00167
- Expected Number of Failures/Squadron during TAT:
 - o Engine: 1.24
 - o Combining Gearbox: 0.45
 - o Transmission: 0.30
 - o Main Rotor Blades: 1.35
- Expected Number of Failures/Squadron/Year:
 - o Engine: 90.34
 - o Combining Gearbox: 3.61
 - o Transmission: 1.81

- o Main Rotor Blades: 16.43

These values were placed in the appropriate cells in the analysis and the acquisition profile worksheets of the spreadsheet model depicted in Appendix A and provide the following results.

b. Scenario 2 Analysis Worksheet Output

The calculations incorporated into the spreadsheet to develop the user-defined values into the required spares and the LCC provided the following critical component analysis.

- Required Spares: (calculated from the relation between Failures/Squadron during TAT and Protection Level)
 - o Engine: 3
 - o Combining Gearbox: 2
 - o Transmission: 1
 - o Main Rotor Blades: 3
- Sparing Based on Poisson Calculations:
 - o Engine: 2
 - o Combining Gearbox: 1
 - o Transmission: 1
 - o Main Rotor Blades: 3
- Average Total Annual Maintenance Cost:
 - o Engine: \$7,687,688
 - o Combining Gearbox: \$180,675
 - o Transmission: \$361,350

- o Main Rotor Blades: \$246,375
- Initial Spares Purchase Cost/Squadron:
 - o Engine: \$2,085,000
 - o Combining Gearbox: \$952,000
 - o Transmission: \$930,000
 - o Main Rotor Blades: \$699,000
- Total Component 20 Year LCC:
 - o Engine: \$213,724,766
 - o Combining Gearbox: \$23,311,782
 - o Transmission: \$39,300,641
 - o Main Rotor Blades: \$39,869,080
- Combined 4-Component LCC: **\$315,206,269**

Analysis of these figures is provided in paragraph D "Analysis of Results" below.

3. Scenario 3: Increased Spares Protection Levels, Peacetime Operational Tempo

This scenario will use scenario 1 baseline reliability figures and cost, but utilize higher protection levels to highlight the cost of bringing higher operational availability (FMC/MC rates) to the warfighters.

a. Scenario 3 User-defined Input Values

Only user-defined input values that have changed between scenario 1 and scenario 3 will be noted.

- Protection Level:
 - o Engine: 0.95
 - o Combining Gearbox: 0.95

- o Transmission: 0.95
- o Main Rotor Blades: 0.95

These values were placed in the appropriate cells in the analysis and the acquisition profile worksheets of the spreadsheet model depicted in Appendix A and provide the following results.

b. Scenario 3 Analysis Worksheet Output

The calculations incorporated into the spreadsheet to develop the user-defined values into the required spares and the LCC provided the following critical component analysis.

- Required Spares: (calculated from the relation between Failures/Squadron during TAT and Protection Level)
 - o Engine: 3
 - o Combining Gearbox: 2
 - o Transmission: 2
 - o Main Rotor Blades: 3
- Sparing Based on Poisson Calculations:
 - o Engine: 2
 - o Combining Gearbox: 1
 - o Transmission: 1
 - o Main Rotor Blades: 2
- Average Total Annual Maintenance Cost:
 - o Engine: \$6,142,950
 - o Combining Gearbox: \$144,540

- o Transmission: \$289,080
 - o Main Rotor Blades: \$197,100
- Initial Spares Purchase Cost/Squadron:
 - o Engine: \$2,085,000
 - o Combining Gearbox: \$952,000
 - o Transmission: \$1,860,000
 - o Main Rotor Blades: \$699,000
- Total Component 20 Year LCC:
 - o Engine: \$205,406,167
 - o Combining Gearbox: \$22,704,857
 - o Transmission: \$46,365,367
 - o Main Rotor Blades: \$45,868,417
- Combined 4-Component LCC: **\$320,344,807**

Analysis of these figures is provided in paragraph D "Analysis of Results" below.

4. Scenario 4: Varying Estimates of Reliability, Increased Operational Tempo

In this scenario we will attempt to analyze the impact of an increase in flight hours that could occur during sustained contingency operations similar to the current Global War On Terrorism. This will be broken down into two parts: Scenario 4a which will be using scenario 1 reliability figures with a 35% increase in monthly flight hours, and scenario 4b which will use the decreased reliability figures of scenario 2 and a 35% increase in monthly flight hours to highlight the compound problem of less reliable components be used more often than expected.

There is a great deal of difficulty in estimating O&S cost when flight hours are higher than expected. As explained in the NAVAIR O&S Handbook from FY02: [Ref 8]

All unit level consumption elements are first normalized to a cost per flight hour. This is because POL, O&I-Level consumables, Aviation Depot Level Repairs (AVDLRs) and Training Expendables are usually thought of in terms of the quantity used per operating hour, and, by extension, cost per flight hour. Additionally, the normalized value would not change with an increase or decrease in the number of flight hours flown in a given period of time. We would, however, expect a squadron's annual cost for these elements to increase if it flew more hours. Normalizing consumable costs first to a flight hour basis allows the model to readily estimate changes in the annual cost per squadron caused by corresponding changes in the flight hours flown per year.

Although most spare parts levels are based on steady-state flight hours under peacetime conditions, there is always thought given to the increased demands on aircraft during contingency operations.

This thesis is being written during the build-up to, and the disarming of Iraq in the spring of 2003. The current AH-1W and UH-1N will undoubtedly be required to operate at far greater than their normal peacetime flight hours while operations in theater.

Contingency spares packages have been put into place on each of the amphibious ships that these airframes are deployed on and any contingency force sent to a potential conflict will carry with them as many spares as they can muster. But what will this do to the normal spares pipeline? Since the spares ordering process can take up to

six months, and in some cases almost two years from start to finish, will the warfighters have all the parts they need to accomplish their missions and keep their readiness at the level necessary to achieve mission success?

These surge operations are the true test of the accuracy of the program's reliability estimations and will ultimately help or hurt the warfighters mission accomplishment.

a. Scenario 4a (Increased Flight Hours) User-defined Input Values

This scenario will keep user-defined variables other than annual flight hours unchanged compared to scenario 1.

- Monthly Flight Hours (per aircraft): 30
- MFHBF in hours:
 - Engine: 100
 - Combining Gearbox: 2500
 - Transmission: 5000
 - Main Rotor Blades: 550
- MTBF (in days, calculated from MFHBF):
 - Engine: 100
 - Combining Gearbox: 2500
 - Transmission: 5000
 - Main Rotor Blades: 550
- Failure Rate per day(λ , calculated from MFHBF):

- o Engine: 0.01
 - o Combining Gearbox: 0.0004
 - o Transmission: 0.0002
 - o Main Rotor Blades: 0.00182
- Failures/Squadron during TAT:
 - o Engine: 1.35
 - o Combining Gearbox: 0.49
 - o Transmission: 0.32
 - o Main Rotor Blades: 1.47
- Failures/Squadron/Year:
 - o Engine: 98.55
 - o Combining Gearbox: 3.94
 - o Transmission: 1.97
 - o Main Rotor Blades: 17.92

These values were produced once the increased flight hours were placed in the appropriate cells in the analysis and the acquisition profile worksheets of the spreadsheet model depicted in Appendix A. They provide the following results.

b. Scenario 4a Analysis Worksheet Output

The calculations incorporated into the spreadsheet to develop the user-defined values into the required spares and the LCC provided the following critical component analysis.

- Required Spares: (calculated from the relation between Failures/Squadron during TAT and Protection Level)
 - o Engine: 3
 - o Combining Gearbox: 2
 - o Transmission: 1
 - o Main Rotor Blades: 3
- Sparing Based on Poisson Calculations:
 - o Engine: 3
 - o Combining Gearbox: 1
 - o Transmission: 1
 - o Main Rotor Blades: 3
- Average Total Annual Maintenance Cost:
 - o Engine: \$8,376,750
 - o Combining Gearbox: \$197,100
 - o Transmission: \$394,200
 - o Main Rotor Blades: \$268,773
- Initial Spares Purchase Cost:
 - o Engine: \$2,085,000
 - o Combining Gearbox: \$952,000
 - o Transmission: \$930,000
 - o Main Rotor Blades: \$699,000
- Total Component 20 Year LCC:
 - o Engine: \$225,449,465

- o Combining Gearbox: \$23,587,658
- o Transmission: \$39,852,392
- o Main Rotor Blades: \$39,245,273
- Combined 4-Component LCC: **\$328,134,787**

Analysis of these figures is provided in paragraph D "Analysis of Results" below.

c. Scenario 4b (Increased Flight Hours and Decrease Reliability) User-defined Input Values

Using the contingency operating hours described in scenario 4a plus the reliability figures used in scenario 2, we will highlight the potentially compounding problem associated with higher than expected operating hours coupled with lower than expected reliability figures.

Only user-defined input values that have changed between scenario 2 and scenario 4b will be noted.

- Monthly Flight Hours (per aircraft): 30
- MFHBF in hours:
 - o Engine: 80
 - o Combining Gearbox: 2000
 - o Transmission: 4000
 - o Main Rotor Blades: 440

These values were placed in the appropriate cells in the analysis and the acquisition profile worksheets of the spreadsheet model depicted in Appendix A and provide the following results.

d. Scenario 4b Analysis Worksheet Output

The calculations incorporated into the spreadsheet to develop the user-defined values into the required spares and the LCC provided the following critical component analysis.

- Required Spares: (calculated from the relation between Failures/Squadron during TAT and Protection Level)
 - o Engine: 4
 - o Combining Gearbox: 2
 - o Transmission: 2
 - o Main Rotor Blades: 4
- Sparing Based on Poisson Calculations:
 - o Engine: 3
 - o Combining Gearbox: 1
 - o Transmission: 1
 - o Main Rotor Blades: 3
- Combined 4-Component LCC: **\$366,920,342**

Analysis of these figures is provided in paragraph D "Analysis of Results" below.

D. ANALYSIS OF RESULTS

As has been shown through the various scenarios presented in this thesis, it is the reliability figures that are the most important in the relationship between spares levels, protection levels, and O&S costs. The analyses of the results above highlight this fact and were a revelation to the author.

1. Scenario 1, Current Reliability Estimates, Peacetime Operational Tempo

- Combined 4-Component LCC: **\$286,763,529** (baseline)

Since the figures used in the model were the historic figures provided by the program, we expected to achieve an output similar to levels seen within the program for recent years. Through discussions with various members of the H-1 Program Team at PMA-276, there was disagreement over some of the figures within the model reflecting accurate annual costs. Specifically, attempting to divide the annual operating cost down to a specific critical component is difficult since so many variables contribute to overall support cost. Nonetheless, program team members generally agreed that the thesis model was taking into account reasonable assumptions and that the output, while not a perfect reflection of historical O&S cost figures, would be adequate for comparison purposes.

The critical component analysis presented in scenario 1 allows the reader to see the relationship between the inputs to the spreadsheet model and the outputs in the spares levels and LCC. While it was not surprising to discover that the LCC for the current spares levels are high, this will be discussed with the Program office and examined more thoroughly upon completion of this thesis.

2. Scenario 2, Decreased Estimates of Reliability, Peacetime Operational Scenario

- Combined 4-Component LCC: **\$315,206,269**
- Change From Scenario 1: **\$28,442,740**

As we have discussed previously in this thesis, tendencies to overestimate reliability figures can lead to

significantly higher LCC. Again, this points to the fact that accurate reliability estimates are important, but actual reliability is the most important.

Scenario 2 made for an interesting contrast with scenario 1 as the decreased reliability estimate that we input into the model yielded a cost penalty of over \$28 Million dollars, a 10% increase. At the current cost per aircraft, this would allow the program to buy two more aircraft, significant quantities of ordnance, or mission equipment to expand the capabilities of the aircraft.

When asked how they would avoid this potential decrease in reliability, the members of the H-1 Upgrade program stated that they are using methods common within the Naval Aviation acquisition system to constantly improve reliability. Some of these methods take into consideration the inherent increase in reliability through testing based on reliability growth. This is achieved with engineering, research, development, Test-Analyze-and-Fix (TAAF), and/or Test-Analyze-and-Redesign (TAAR) procedures until the product passes its acceptance tests and/or is delivered to the end user.

We were clearly advised by the program office that the estimations of reliability were just that, only estimations. Hopefully, demonstrating to the program Team members the sensitivity of protection levels and O&S costs to the failure rate estimations will emphasize the fact that reliability is an excellent investment and must not be an afterthought.

3. Scenario 3, Increased Spares Protection Levels, Initial Estimates of Reliability, Peacetime Operational Tempo Scenario

- Combined 4-Component LCC: **\$320,344,807**
- Change From Scenario 1: **\$33,581,278**

The changes caused by the increased protection level were not reflected on the analysis worksheet, but were instead evident on the acquisition profile worksheets for each component. Seeking to provide this additional protection against stockout, the program office would have to buy significantly more spares over the lifetime of the program. This is what caused an increase of over \$33 million compared to the lower protection level.

Requiring and applying a higher protection is the equivalent of buying a premium insurance policy with a low deductible. The risk of stockout is not borne by the operator, but by the program. There is always a possibility that a stockout could still occur, but the probability is significantly lowered with the higher protection level.

When initial estimates of reliability are uncertain, a program should consider increasing the protection levels until actual reliability figures emerge. Adjustments can then be made as necessary, all the while keeping the aircraft flying. However, the increased costs of higher protection levels, as displayed in Scenario 3, show the trade-off decisions that are required by the Program Manager when operating with limited resources. Sometimes, risks must be taken.

4. Scenario 4a, Current Estimates of Reliability, Contingency Operational Tempo

- Combined 4-Component LCC: **\$328,134,787**
- Change From Scenario 1: **\$41,371,258**

The purpose of Scenario 4a was to give the reader a feel for how sustained contingency flight operation, or higher than expected overall flight hours, could affect the spares levels and LCC of an aviation program.

Based on the unchanged failure rate and increased flight hours, the spares levels and LCC changed significantly from scenario 1. Through a 35% increase in flight hours, the overall LCC with respect to these 4 components increased by over \$41 Million, or nearly 13%. If this carries through to other aspects of the program, huge increase in overall LCC could be incurred by a small increase in average operating hours. Therefore, planning for all aspects of support for a given platform are highly dependant on expected usage rates.

One thing that is not taken into account in this model, however, is the slow reaction time of the industrial base to the initial surge in flight hours and increased demand for spares. It is precisely at this moment when the pressure is really on the O-Level maintainers to keep the aircraft operating. Frequently, this may have to be accomplished through cannibalization, although this comes at the cost of wasted maintenance time (removing RFI components from other aircraft to replace Non-RFI components already removed, and then installing both the cannibalized component and the replacement RFI component

when it is finally received) and subsequent lower morale among the maintenance Marines.

5. Scenario 4b, Reduced Estimates of Reliability, Contingency Operational Tempo

- Combined 4-Component LCC: **\$366,920,342**
- Change From Scenario 1: **\$80,156,813**

The purpose of Scenario 4b was to give the reader a feel for how higher than expected overall flight hours, coupled with lower than expected reliability could severely affect the spares levels and LCC of an aviation program.

This is a worst-case scenario for any program. The combined blows of higher than expected usage as described in scenario 4a above in conjunction with lower than expected reliability as described in Scenario 2. With the 20% decrease in reliability and the 35% increase in usage, the program was suddenly faced with a 28% increase in LCC for the four components described.

This scenario was the most meaningful to the author due to the realization that any program that begins estimating LCC with overly optimistic estimations of reliability and usage could end up costing the taxpayer significantly more than anyone expected and jeopardize the very existence of their program.

E. RECAPITALIZATION

The findings presented here are based on a system life of 20 years from IOC. From past experience in the Marine Corps and other services, some airframes (such as the B-52 and the CH-46) continue operating well past this service

period. To take this possibility into account would require reworking the spreadsheet model to allow for longer life span and related LCC.

During the life cycle of any system, there comes a time when the decision has to be made to either phase-out or revitalize the system through a Service Life Extension Program (SLEP) or Mid-Life Upgrade (MLU). This is a difficult decision, especially during times of great fiscal austerity.

The basis for the H-1 Upgrade program described in this thesis was born of a MLU for the UH-1N. The Huey has lost a significant portion of its combat load, performance, and mission radius over the course of three decades due to added mission equipment and degraded engine performance. It was decided in the early 1990s that both aircraft could benefit from upgrading both platforms to recapture the commonality they once had.

The Marine Corps Aviation Master Plan has The H-1 program being replaced by the "Joint Replacement Aircraft" (although no one know what that will look like) starting in the year 2020. Given the uncertainty of this time estimate and historical trends to "do more with less for longer," the potential for recapitalization of the new AH-1Z and UH-1Y is high.

F. CHAPTER SUMMARY

As has been discussed in this chapter, we utilized the information presented in Chapters II and III to allow the author to draw conclusions based on an analysis of the information gathered. Inputs into the spreadsheet were described for the four scenarios and the results of those

inputs noted. Through these results and their analysis, the author will attempt to draw conclusions for presentation in Chapter V.

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V. CONCLUSIONS AND RECOMMENDATIONS

A. CHAPTER OVERVIEW

In this chapter, we will discuss the analyses, conclusions, and recommendations presented by the research conducted for this thesis.

B. ANSWERS TO RESEARCH QUESTIONS

While there are many areas that have been covered in the course of this thesis, there are also many areas that need to be investigated in more detail. By examining the list of research questions stated at the beginning of this thesis, we can begin to see where light has dawned and where gray areas still exist.

1. Primary Research Question

- *How are reliability estimations and planned spares levels related to Life Cycle Costs in a MDAP?*

Analysis: There is a direct connection between reliability estimates, spares levels, and LCC as established by the scenarios run in this thesis. The surprising aspect was the degree of interdependence that each of these factors has. During scenario 2 when we decreased the reliability of the components analyzed, we found a significant increase in LCC.

With a 20% decrease in the overall reliability of these 4 components, we saw a 10% increase in their overall LCC. This translates into huge penalties for a program with a current TOC of over \$14 Billion and with hundreds of parts requiring spares. As can be deduced from the cursory

findings in this thesis, reduced reliability equals increased cost in both material and labor.

Therefore, increased reliability is to the benefit of everyone who develops systems for Naval Aviation, especially the operators and maintainers of these systems once they are fielded.

Conclusion: There is a direct relationship between poor reliability estimations, inadequate spares levels, and higher than expected LCC.

Recommendation: Additional emphasis needs to be placed on reliability throughout the acquisition establishment. Initiatives such as Performance Based Logistics and advanced reliability modeling methods need the backing of senior leadership armed with an understanding that reliability isn't everything, it's the only thing.

2. Secondary Research Questions

- *What methods are being used by the H-1 Upgrade program to improve overall reliability and availability?*

Analysis: When the author approached the H-1 Upgrade Program PM with this question, the following response was given:

As with all areas in the development of a weapon system, the PM assigns responsibility for specific areas to his agents. He has funded and tasked a team to be solely responsible for reviewing, monitoring, documenting and recommending changes for all reliability issues. All issues are documented and resolutions are identified. Unfortunately reliability is competing with many other requirements for

limited budget and schedule resources and when issues are identified there is not always funding or schedule available for the correction of deficiencies at the time that the issues are identified. Corrections to deficiencies are documented and then the responsible IPT [Integrated Product Team] will do the analyses required to determine the most cost efficient and appropriate time for incorporation of the changes. Unfortunately some of the reliability recommendations may never make the incorporation list as the Business Case Analyses may not show the return on investment required to fund the modification.

The H-1 Upgrade program is using methods common to Naval Aviation acquisition to improve reliability and availability. Some of these methods take into consideration the inherent increase in reliability through testing based on reliability growth. This is achieved with engineering, research, development, Test-Analyze-and-Fix (TAAF), and/or Test-Analyze-and-Redesign (TAAR) procedures until the product passes its acceptance tests and/or is delivered to the end user. Reliability growth is related to factors such as reliability requirements, initial reliability level, reliability funding and management, corrective actions, and competitive factors.

The goals set forth by the H-1 Upgrade Program for individual spares are based on the critical nature of each of those components. Currently, the program is using simulation within the ARROWS model to plan protection levels of at least 80% for components considered critical for meeting their reliability requirements. This is very important as it recognizes the relationship between these

critical components and the role they play in maintaining and possibly increasing Ao for the systems.

Conclusion: Even though an apparent emphasis is being placed in reliability, an effective program to reward the achievement of higher reliability is not in place.

Recommendation: While the Program Manager uses metrics for cost, schedule, and performance to meter out rewards or reprimands to the contractor during the development of the product, a long-term reward system should be put into place to share some of the profits from higher than expected reliability. PBL is the first step in this direction, but a direct monetary incentive would hit the contractor in their bottom line and make all of industry takes notice.

- *How is reliability measured in general and by the H-1 Upgrade Program specifically?*

Analysis: As was discussed in Chapter II of this thesis, the mathematical computation of reliability is based on the MTBF of the systems being measured.

The H-1 Upgrade Program Team is using similar measurements for reliability and availability. Unfortunately, since the system is still undergoing developmental and operational testing, there is no current data for the overall system or certain critical components in an actual operational environment. In other words, they are still using predicted reliability to make their assessments of availability for the system users. The program office is also using historical data from similar systems to give additional credibility to their

estimations. This is important since this provides the greatest insight into potential pitfalls of underestimating reliability for critical component later on.

Conclusion: Predictions of reliability are a necessary evil that every new MDAP must contend with when bringing a new system to the field. Even a Commercial Off The Shelf (COTS) item will need to have its reliability predicted for the harsh environment that the military would use it in compared with that of a commercial consumer.

- *What information about reliability and availability will be of greatest use to the PM to help make more informed decisions about O&S cost allocations?*

Analysis: When the author approached the H-1 Upgrade Program PM with this question, the following response was given:

All of the reliability and availability data being delivered to the government through the supportability analysis process is important to the PM for making decisions concerning supportability. But none is more important than the other. All data is considered. The availability and reliability data is initially delivered to the government from the contractor through the Supportability Analyses process. The initial numbers are engineering predictions and some of the initial logistics support planning is done using these predictions. But, as the systems mature and as actual data is collected then the maintenance planning and logistics support planning is updated to reflect actual availability numbers. So for the PM, through his agents [logistics support personnel], all of the data delivered through the Supportability Analysis (SA) is very important in the decision making process for the Program, but none carries more weight than another. The types of data used are mean times between failures, mean times to

repair, Ao, material replacement rates, and reliability centered maintenance data. Each data type is used in a different way, e.g., mean times for repair and failure data determine the sparing levels for spare parts, reliability centered maintenance data will help determine the IMC (Intermediate Maintenance Concept) and SDLM (Scheduled Depot Level Maintenance) requirements, etc.

This was followed with a question about Performance Based Logistics (PBL), which is starting to make Naval Aviation acquisition place greater emphasis on reliability:

The H-1 Program is in the initial stages of determining its PBL concept and an emphasis will be placed on reliability and availability, but LCC will still be a factor in the development of the PBL strategy. The PBL Warfighter Agreement for the H-1 program has not yet been defined and that is the document that will spell out the specifics for the reliability, availability and LCC requirements.

Conclusion: Methods are being explored by the PM to emphasize higher reliability. This is an encouraging development for all members of the H-1 Upgrade Program and the eventual users of the system. Any method to place greater emphasis on reliability will benefit all concerned parties and should be investigated. Unfortunately, it is also clear that reliability cannot be the sole focus of the busy PM.

Recommendation: The program office needs to continue pursuing PBL and other methods to place emphasis on higher reliability. Additionally, greater emphasis needs to be placed on obtaining more accurate reliability predictions.

- *What is the impact on LCC and spares levels if the flight hours are more than planned?*

Analysis: The purpose of Scenario 4a was to give the reader a feel for how sustained contingency flight operation, or higher than expected overall flight hours, could affect the spares levels and LCC of an aviation program. Based on the unchanged failure rate and increased flight hours, the spares levels and LCC changed significantly from Scenario 1. Through a 35% increase in flight hours, the overall LCC with respect to these 4 components increased by over \$41 million, or nearly 13%. If this carries through to other aspects of the program, huge increase in overall LCC could be incurred by a small increase in average operating hours. Therefore, planning for all aspects of support for a given platform are highly dependant on expected usage rates.

Conclusion: Unfortunately, purchasing of spares is not as flexible for the program office as increasing flight hours is for the operational units. Therefore, in the interest of buffering the impact of flight hour surges due to potential hostilities, all Naval Aviation programs are required to purchase more spares for contingencies than they would need for sustained peacetime operations. These spares are kept in "Contingency Spares Pack-ups" (CSPs) that take up the slack in the normal spares pipeline to allow the program office time to order and ship more spares when demand spikes. These CSP spares are regularly rotated out of and back into the normal spares system during peacetime to maintain their "freshness."

The short-term results of increased flight hours due to surge operations is a higher price for the spares that are ordered to replace those that are being taken out of the Cusps. Contractors need to accommodate the greater demand by possibly opening additional assembly lines, hiring new employees, or requiring their current employees to work extra hours. These costs are passed along to the program office (and the Fleet) through the increased price for the required spares.

Recommendation: During times of higher than "average" usage rates, such as the current Global War on Terrorism, each program office should reassess its spares levels just as it should regularly do when better reliability estimates are available. While no one can predict how long this higher optempo will last, these are the times when it is imperative that the warfighters have all the spares they need to achieve mission accomplishment.

- *After system fielding, how are spares levels adjusted as estimations of reliability are replaced by actual reliability figures of merit?*

Analysis: In an excerpt from the first PM quote above:

Corrections to deficiencies are documented and then the responsible IPT will do the analyses required to determine the most cost efficient and appropriate time for incorporation of the changes. Unfortunately some of the reliability recommendations may never make the incorporation list as the Business Case Analyses may not show the return on investment required to fund the modification.

As reports from the system maintainers at the O-Level and I-Level begin to report on the actual MTBF and reliability of components, monthly feedback through the Reliability and Maintainability Office at NAVAIR highlights these figures of merit (FOM) to the program office. If the FOM are within a certain tolerance of the predicted reliability of the component, then nothing is done until the FOM are subsequently reviewed.

If a critical component is below the tolerance set by the Deputy Program Manager for Logistics (DPML) at the program, a review of the reasons for the discrepancy is initiated. This process could take several months as interviews are conducted, statistics are reviewed, and maintenance practices scrutinized. In the meantime, parts shortages may mount as the supply system expends any remaining spares that may be available. Cannibalization of good parts from other aircraft increases as the needs of the user to meet operational requirements is hampered by the lack of spares. Also, the call for an increase in spares is not instantaneous and requires significant lead time by the suppliers to manufacture the additional requirements.

Unfortunately, a cautious attitude at the program office concerning dedicating additional funds to shoring up this shortfall may only compound the situation.

The demonstration of reduced reliability in Scenario 3 does not take into account the "worst case scenario" that has been demonstrated within other acquisition programs in Naval Aviation, such as the F/A-18 TEF actuator cited in Ref 4. Should the H-1 Upgrade Program experience one of

these extremely poor performing critical components, all aspects of the program support structure may be affected.

Conclusion: Adjustment of spares level requirements is a complicated task that may not receive the proper emphasis on a busy program, even when significant cost benefits can be realized.

Recommendation: An independent reliability monitoring structure within the acquisition community should be established that has the sole purpose of matching actual reliability information with programmatic parts sparing. Eventually, recommendations from this entity could be evaluated by the program office to determine whether adjustment of spares levels are warranted.

C. AREAS OF FURTHER RESEARCH

As has been stated previously in this thesis, there are many interesting areas that have been touched on only lightly, but that would benefit all acquisition programs with additional research.

Additional study of initial investment versus LCC would highlight to members of the acquisition community that, even though it is politically unpopular to put greater emphasis on reliability research funding during EMD, this could save the entire DoD and Federal Government huge amounts of money as O&S cost savings are realized.

Another difficult truth for all acquisition professionals to bear is that full disclosure of LCC early in a programs development can lead to critical review and possibly elimination of the program. Therefore, as was touched on briefly in this thesis, initial reliability

estimations may be overly optimistic in accordance with the overall savings they create in the estimated LCC of the program.

Lastly, new initiatives designed to provide greater transparency to Total Ownership Cost (TOC) and highlight key investments such as Performance Based Logistics (PBL) and Navy Visibility and Management of Operating and Support Cost (VAMOSC) Personnel Universe are vital for everyone from the PM to the Secretary of Defense to clearly see where the best investment of DoD dollars can be found. PBL is taking hold within the NAVAIR acquisition community and will play a major role in the future as programs vie for tight resources.

PBL is attempting to make use of Ao as a KPP for programs within DoD. The results of the initial efforts at this should be provided further study and greater visibility for the acquisition community to understand the benefits of emphasizing reliability at a programs outset.

D. SUMMARY

A variety of conclusions have been reached as a result of this research. Some conclusions may have an impact on the H-1 Upgrade Program specifically and some on the DoD acquisition community in general.

The desire to push a program through to LRIP with minimal initial investment has placed greater emphasis on lowering investment during the EMD phase, to the detriment that the greater investment would have on keeping down costs during the O&S phase. In other words, a program can look more attractive now by spending less up front and hoping that reliability growth curves will be met or

exceeded in production. This problem has been identified in other publications, but may still be haunting the acquisition field within Naval Aviation.

The H-1 Upgrade Program may be falling into the above-mentioned trap. It is faced with the dilemma of needing to look "lean and mean" when pushing forward to Milestone C, but may be putting off cost until the time comes to pay the O&S bills. Without proper emphasis on high reliability for critical components (and the overall system) in the beginning, the amazing helicopters that the program office is developing may be inoperable when they are needed most due to overestimations of reliability and a subsequent lack of spare parts.

As a whole, if Naval Aviation continues to overestimate reliability and underestimate LCC during the initial phases of an acquisition cycle, all programs may suffer from a lack of trust with the American public and the DoD Acquisition establishment. Also, one of the hidden costs of poor reliability estimates is the deteriorating morale of the maintainers who must work longer hours than necessary to accomplish redundant work when having to cannibalize parts due to shortages. It is on the backs of these Marines that our Nation maintains its edge and its ability to carry the torch of Freedom around the world.

Within the scope of this thesis, we have discussed the impact of inaccurate reliability estimates and unforeseen flight hour increases on the LCC of the components we chose to analyze. Through analysis of the interaction of these factors we have come to the conclusion that reliability should be the main emphasis of this (and any other)

program. There can be severe repercussions to misunderstanding the importance of reliability in the life cycle of any program.

Right now, within the DoD and Naval Aviation acquisition, steps are being taken (such as PBL) to ensure the proper emphasis is being placed on reliability within our programs. This emphasis is crucial, not only to the warfighters who need their equipment to operate properly when it is needed, but to every taxpayer in the nation who want more accountability and typically wants the DoD to do more with less. By understanding that increased reliability is a sound investment in a program's future and the DoD's future, our leadership will insist from now on that reliability isn't everything, it's the only thing.

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APPENDIX

1. SPREADSHEET MODEL

a. Scenario 1 (baseline)

The following cells are a screen capture of the worksheets using the inputs from scenario 1 in Chapter IV.

Reliability, Spares, and Protection Level Analysis							
Aircraft Per Squadron	27						
Monthly Flight Hours	22						

Table 4. Analysis Worksheet Input/Output

Per I-level				Repair TAT	Failures/ Sqn	Failures/ Sqn
Critical Component For Analysis	MFHBF	MTBF (days)	λ	(Days)	During the TAT	Per Year
T700 Engine	100	136.36	0.00733	5	0.99	72.27
Combining Gear Box	2500	3409.09	0.00029	45	0.36	2.89
Main Transmission	5000	6818.18	0.00015	60	0.24	1.45
Main Rotor Blades	550	750.00	0.00133	30	1.08	13.14

Table 5. Analysis Worksheet Input/Output

	Required Spares(Norm)	
Protection Level	Norm	Poisson
0.850	3	2.000
0.850	1	1.000
0.850	1	1.000
0.850	3	2.000

Table 6. Analysis Worksheet Input/Output

	Avg Annual Maint	Avg Total Annual	Initial Spare Purchase	Total Component
Unit Acq Cost	Cost/ Failure	Maint Cost	Cost per Sqn	20 Yr LCC
\$ 695,000	\$ 85,000	\$ 6,142,950	\$ 2,085,000	\$ 187,930,428
\$ 476,000	\$ 50,000	\$ 144,540	\$ 476,000	\$ 22,704,857
\$ 930,000	\$ 200,000	\$ 289,080	\$ 930,000	\$ 38,086,790
\$ 233,000	\$ 15,000	\$ 197,100	\$ 699,000	\$ 38,041,454
			Total	\$ 286,763,529

Table 7. Analysis Worksheet Input/Output

Tables 4, 5, 6, and 7 combined are the "Analysis" worksheet combining all the user inputs and the calculations from the individual component worksheets described in scenario 1 and shows the total LCC for scenario 1.

Tables 8, 9, and 10 are screen captures of the "Acquisition Profile" worksheet (in this case the engine, but nearly identical to the other components except for individual costs) used to calculate the LCC of the individual components using scenario 1 inputs.

Current H-1 Program Acquisition Profile/ Engines				
Fiscal Year	2004	2005	2006	2007
UH-1Y Produced	2	0	3	6
AH-1Z Produced	3	0	2	4
Total AC Produced/ Year	5	0	5	10
Total AC Inventory	8	5	10	20
Total FY I-Level Spares Purchase	2	2	2	5
Total Spares (barring attrition)	2	4	6	11

Table 8. Acquisition Profile Worksheet Input/Output

Years of Operation	1	2	3	4
Initial Spares Purchase	\$ 1,390,000	\$ 1,390,000	\$ 1,390,000	\$ 3,475,000
Annual Maintenance Cost	\$ 6,142,950	\$ 6,142,950	\$ 6,142,950	\$ 6,142,950
Total (FY2004)	\$ 7,532,950	\$ 7,532,950	\$ 7,532,950	\$ 9,617,950
Inflation (Then Year)	\$ 7,834,268	\$ 8,147,639	\$ 8,473,544	\$ 11,251,641
PV (FY2004)	\$ 7,308,086	\$ 7,089,934	\$ 6,878,294	\$ 8,519,944
NPV	\$ 187,930,428			
Inflation Rate	4.00%			
Discount Rate	3.20%			

**Table 9. Acquisition Profile Worksheet
Input/Output**

As can be seen in these tables, the fiscal years from 2008 to 2023 are not shown in these tables but are present in the model. Likewise, the years of operation from year 5 to year 20 are also not shown.

2024	2025	2026	2027	Totals
0	0	0	0	102
0	0	0	0	183
0	0	0	0	285
285	285	285	285	285
2	2	2	2	165
159	161	163	165	165
21	22	23	24	
\$ 1,390,000	\$ 1,390,000	\$ 1,390,000	\$ 1,390,000	
\$ 6,142,950	\$ 6,142,950	\$ 6,142,950	\$ 6,142,950	
\$ 7,532,950	\$ 7,532,950	\$ 7,532,950	\$ 7,532,950	
\$ 17,165,846	\$ 17,852,480	\$ 18,566,579	\$ 19,309,242	
\$ 3,986,343	\$ 3,867,348	\$ 3,751,905	\$ 3,639,908	

**Table 10. Acquisition Profile Worksheet
Input/Output**

Both of these worksheets are used for all the different scenarios by modifying the user inputs.

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